V entilation
I nformation
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n° 5

June 2004

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International Energy Agency
Energy Conservation in Buildings
and Community Systems Programme

Air Infiltration and Ventilation Centre

Displacement Ventilation

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1 Introduction

1.1 Definitions

Mixing ventilation: This is the most common air distribution method, involving supplying ventilation air to the room at high velocity, causing the air in the room to be well mixed with fresh air.

Occupied zone: The spatial volume within the room that is frequently occupied by people. It is 1.3 ~ 1.8 m high (sitting/standing people) and not closer than 0.3 ~ 1.5 m from the walls.

Draught-risk zone (near-zone): The region near the supply diffuser where occupants experience discomfort due to cold draught along the floor (illustrated by red isovels in Figure 1, Figure 7, Figure 8).

1.2 Principle of function

The principle involves air supply and distribution in a room by upwards displacement, i.e. as direct as possible through-flow in the occupied zone in order to achieve high ventilation efficiency. In addition, air distribution by displacement generally makes it possible to supply a larger quantity of air than for conventional mixing ventilation, which requires concentrated supply at high velocity.

The air flow pattern differs greatly from that caused by conventional mixing supply jets. Air is supplied at low velocity to the occupied zone, often near the floor (Figure 1). The new air is slightly cooler than the air in the room, and thus has a strong tendency to fall and spread out over the floor in a uniformly thin layer (approximately 20 cm), due to gravity,

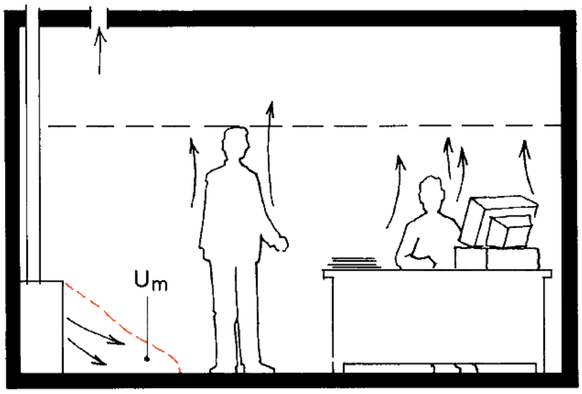

Figure 1: Principle of displacement ventilation. Air in occupied zone becomes both heated and polluted by occupants etc., and rises upwards due to natural convection.

without mixing significantly with the room air above. This process leads to a continual upwards uniform displacement of air in the room, akin to filling a bathtub with water.

The air in the occupied zone is thus generally fresher than for mixing ventilation. Air is extracted from the room at ceiling level.

In addition, for localized pollutant sources that generate heat, such as humans, the released pollutants rise rapidly to above the occupied zone, due to buoyancy forces (an upwards flowing natural convection plume). This local upwards flow also brings up a steady stream of fresh air from the floor up to the breathing zone of occupants. The air in the breathing zone is thus slightly fresher than elsewhere in the room at the same height.

The supplied air flow rate and its cooling capacity are limited by the size of the air supply areas, and on the magnitude of the air flow rate that is technically/economically justifiable. The cooling capacity is also limited by how cold the supply temperature can be without causing local discomfort (cold draught along floor).

1.3 Applications and limitations

Displacement ventilation is only appropriate where the supply air should be cooler than the room air, and where the contaminants are warmer and/or lighter than the surrounding air in the room. Displacement ventilation is therefore well suited for achieving good air quality in occupied spaces. Well-designed displacement ventilation is superior to mixing ventilation in rooms with a high occupancy density, e.g. restaurants, classrooms, and meeting rooms. High ceilings further improve the ventilation efficiency of displacement ventilation, e.g. conference rooms, theatres, supermarkets. More generally, displacement ventilation is preferable where a large air flow rate is required in a small room, or for ventilation of tall rooms (above 3 metres).

Mixing ventilation is often a better choice than displacement ventilation in rooms where air quality is not an issue, or in cellular offices. Displacement ventilation may be less preferable than mixing ventilation in the following cases [1]:

- Where the main pollutants are denser/colder than the ambient air (e.g. particulate, dust)
- Where overheating is the main problem, not air quality
- Where ceiling height is below 2.3 metres
- Where continued very significant movement disturbs the air flow in the room
- If the main problem is cooling, in rooms with low or normal ceiling height (e.g. offices), mixing ventilation with a chilled ceiling is recommended.
- Mixing ventilation is widely used for common applications, i.e. for air flow rates below approx. 10 ℓ/s·m².

Figure 2 summarizes the differing areas of application of displacement and mixing ventilation, both with or without chilled ceilings [3]. This figure is a rough guide as to the best system giving the least draught.

The main performance advantages of displacement ventilation over mixing ventilation are [1]:

- Less cooling needed for a given temperature in the occupied zone
- Longer periods with free cooling
- Better air quality in the occupied space (though there can be more airborne respirable dust in the breathing zone [3])

The main weak points of displacement ventilation are [1]:

- Risk of cold sensation or draught near the floor. Preventing this requires proficient design skills.
- Wall-mounted diffusers can take up much space, and must not be blocked by furniture along the wall. Freestanding furniture in the room poses generally no problem, as the supply air can flow around it or underneath it, akin to water filling a bathtub.
- Wall-mounted diffusers permit little flexibility in changes in layout during building's lifetime. There must be close collaboration between architect and HVAC designer to find suitable locations for diffusers.

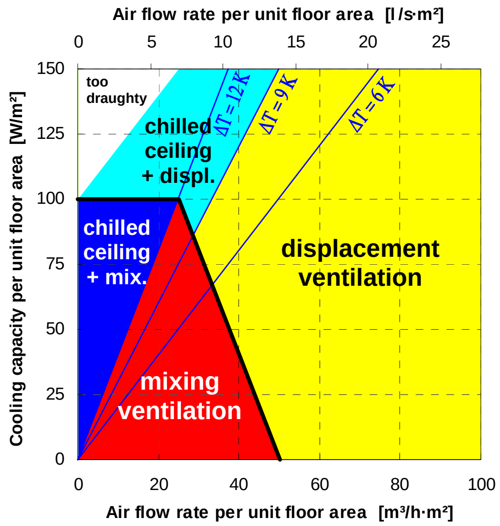

Figure 2 : Appropriate ventilation systems for different flow rates and heat loads [3]. The "ΔT" lines are temperature difference between room and supply air when ventilation alone is used for cooling.

When displacement is combined with a chilled ceiling, the supply air temperature should be constant, while the cooling output is controlled by flow rate adjustment in the chilled ceiling.

2 Types and their properties

2.1 Floor-standing diffusers for horizontal flow

This is the most common type of displacement ventilation. It is illustrated in Figure 1. This principle requires that the supply air is always at least 1°C below the room air temperature (see also point 3.1.1). The number of diffusers in the room (more specifically, the total horizontal perimeter of diffusers) limits the total ventilation rate that can be achieved without causing draught.

There are 3 main types of such supply diffusers:

- Flat, flush with wall, integrated
- Protruding from wall, free-standing: flat-faced, ½-radial or ¼-radial for placing in corners.
- Free-standing in the floor, with duct from ceiling or from below up through the floor

2.2 Under-floor ventilation

Figure 3 illustrates this principle. The limiting design condition is winter, when the supply air must be at least 2°C below the room air temperature in order to achieve effective displacement. The number of diffusers limits the total ventilation rate that can be achieved without causing draught.

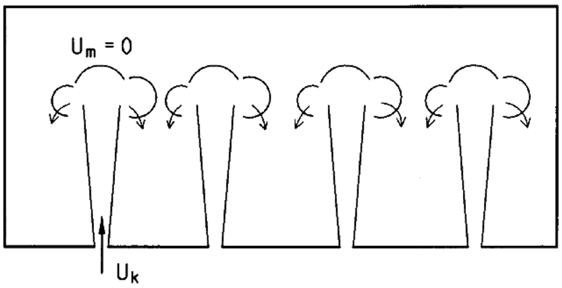

Figure 3 : Under-floor displacement ventilation, e.g. computer rooms with raised floor.

Usually circular outlets are used in a modular raised floor. The outlets are shaped to cause swirl so that the air mixes quickly, causing little draught. This mixing is localised at low level, thus not appreciably reducing the ventilation efficiency.

Air can be supplied though carpet, but the cleanliness of the carpet is an issue.

2.3 Ceiling supply from textile ducts or socks

Such ducts are mostly used in deep open plan enclosures. When the supply air reaches the floor, it spreads out along the floor just as in the gravity current seen in conventional displacement ventilation. The maximum allowable velocity in the falling curtain of supply air, u_m (Figure 4), depends on whether the ducts are above a zone of permanent occupancy or not. If it is a transit zone, or zone infrequent occupancy, then u_m can be up to 0.25 m/s.

Such ducts can alternatively be used as supply terminal devices at floor level, in which case normal design rules for floor-standing diffusers apply.

Some other duct types (not textile) are designed with many small high-velocity jets spaced uniformly along the duct's length. Such installations are documented and designed according to rules for mixing ventilation.

Textile duct systems require a good routine for cleaning the ducts (recommended by the duct manufacturer), and the supply air must be well filtered.

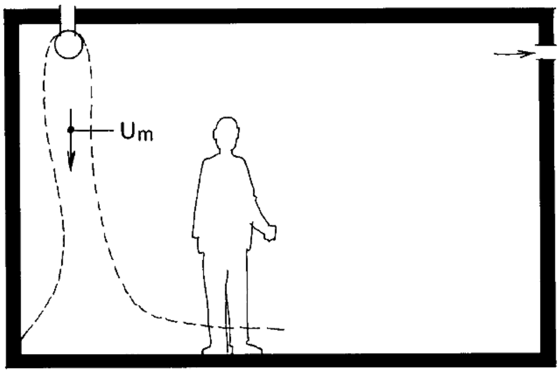

Figure 4: Supply through horizontal textile ducts.

2.4 Downward flow from ceiling supply regions

This specialized air distribution method (Figure 5) is relevant where there is a need to create local regions of fresh air at breathing height or where the floor region is particularly contaminated. These installations are a challenge to design well. An example is operating theatres in hospitals.

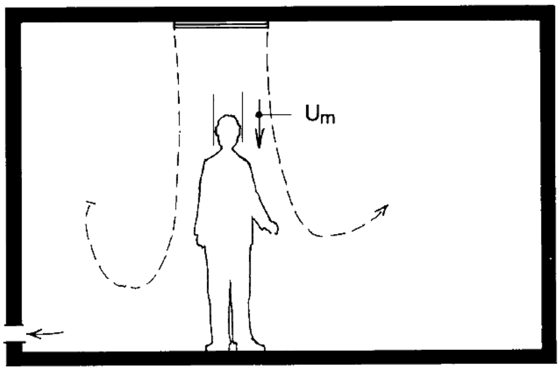

Figure 5: Supply through large areas in the ceiling. Exhaust at floor level.

3 Design procedure

3.1 Thermal comfort constraints

3.1.1 Draught-risk zone and draught risk calculation

By far the most common and significant error that is made in the design of displacement ventilation is that one allows too low supply air temperature (which can happen if the supply temperature is improperly controlled by a room thermostat), or the air velocity along the floor is too large (i.e. if too few supply diffusers are used, such that each diffuser has a larger flow rate). These factors increase the area of the floor that is too draughty for comfort (the draught-risk zone) adjacent to the supply diffusers. The architectural layout must take into account that the floor area within the draught-risk zone of a diffuser is not suitable for permanent occupancy, though it can be a transit zone, for example.

The supply air temperature during periods of occupancy should not fall below 18°C during summer and 19 ~ 20°C during summer, depending on the performance of the diffuser.

The air flow leaving a horizontal supply diffuser will accelerate as it falls to the floor and reach its maximum velocity v_{max} at the point where the cross sectional area of the flow along the floor is smallest (Figure 6). From this point on, the height of the layer of flow along the floor stays uniform (at approx. 20 cm) but the velocity decays with distance from the diffuser.

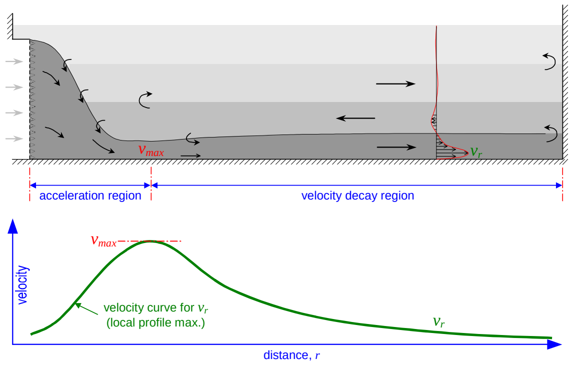

Figure 6: Cross section through flow along floor, from a floor-standing supply outlet.

For diffusers with radial flow (Figure 7), the velocity decay is inversely proportional with distance from the diffuser's central axis (due to the increase with cross-sectional flow area proportional to radius *r*). For linear flow diffusers (Figure 8), the velocity decay is much more gradual (exponential, due to friction & mixing) since the cross-sectional flow area is constant with distance *r*.

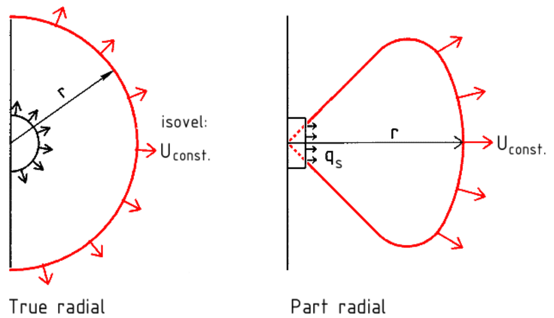

Figure 7: Plan view showing two examples of radial flow pattern along floor: ideal ½-radial diffuser, and a flat-faced diffuser.

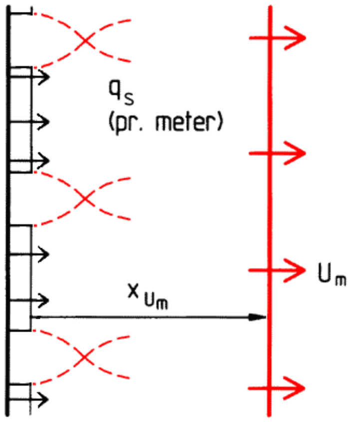

Figure 8: Plan view showing uniform linear flow pattern at some distance from a wall with a continuous diffuser along its length, or regularly spaced wall diffusers.

For diffusers with a radial flow pattern (Figure 7) the relationship between distance and velocity is approximately described by:

$$v_r \approx K_v \left(\frac{q_s \; g \; \Delta T_s}{T_s \; r} \right)^{\frac{1}{3}} \qquad \text{(Equ. 1)}$$

Similarly, for linear diffusers (Figure 8) the maximum velocity is described by:

$$v \approx K_v \left(\frac{q_s \; g \; \Delta T_s}{T_s} \right)^{\frac{1}{3}} \qquad \text{(Equ. 2)}$$

Where:

- v = velocity [m/s]
- K_v = diffuser constant. Typical value is 1.9 for radial and 1.5 for linear diffuser.
- q_s = supply volume flow rate [m³/s]
- g = gravitational acceleration [9.81 m/s²]
- ΔT_s = Supply under-temperature [K]
- T_s = Supply temperature [K]
- r = distance from diffuser's central axis (flow epicentre) (only relevant to radial diffusers)

K_v is not strictly constant, as it is influenced slightly by temperature. For more accurate equations with improved constants, see [4].

To prevent discomfort due to draught, the air velocity along the floor in the occupied zone should not exceed 0.15 m/s in winter and 0.25 m/s in summer ([8] or [9]).

The local air temperature has a very significant influence on the level of discomfort due to draught. One should therefore consider conducting design calculations of draught-risk using the Draught-Risk (DR) relationship given in [10]. Acceptable boundary values of draught-risk for different classes of indoor environment are given in [9].

3.1.2 Temperature stratification

In displacement ventilation, the air temperature increases from floor to ceiling. This means that the occupied space is cooler than the air above. Thus, compared to mixing ventilation, the supply air temperature can be approx. 1 ~ 2°C higher for rooms of height 3 m, and up to 4°C for tall rooms. This gives longer periods of the year where free cooling can be applied, and at other times less energy is needed for cooling the supply air, compared to mixing ventilation.

In most applications in rooms of normal height, it is possible to assume a linear vertical temperature profile from the floor, and that the air temperature at floor level is half-way between the supply and extract temperatures (the "50% assumption", see Figure 9). For more accurate calculations of vertical temperature profile, see [5].

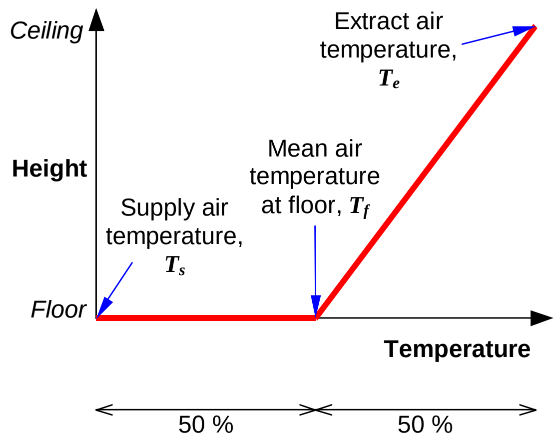

Figure 9: Illustration of the 50% assumption.

The temperature gradient should not exceed 3°C between feet and the torso (from 0.1 and 1.1 m) ([8] or [9]).

3.2 Air quality constraints

3.2.1 Ventilation efficiency in practice

Displacement ventilation can work with lower ventilation rates than mixing ventilation. This is because it has a better ventilation efficiency. This applies to both:

- *air quality* (local contaminant removal efficiency in the breathing zone ≈ 120%)

- and *temperature* efficiency (i.e. heat removal efficiency in the occupied zone; see point 3.1.2).

However, when a very low ventilation rate and large under-temperature is used, mixing ventilation is preferable. Normally, both mixing and displacement ventilation systems require about the same air flow rates, in which displacement ventilation usually gives a better air quality for the same amount of air.

3.2.2 Pollution layer height

The height of the pollution layer depends on the ventilation rate and the strength of convective heat sources in the room. The supply flow rate should be designed to be sufficiently large that the pollution layer is kept above occupied zone (Figure 1). These calculations are described in [1].

4 Design issues

4.1 Space heating

Displacement ventilation cannot be used in cases where the room is heated primarily with the ventilation air (i.e. where the supply air is warmer than the room air). The air in the occupied zone would become stagnant because the warm supply air would rise straight to the ceiling and be exhausted (short-circuiting).

It is suitable to use displacement ventilation in combination with space heating by means of radiators (e.g. placed below windows, with a large area), radiative ceiling heating, or floor heating. Ceiling heating is particularly complementary. Concentrated convective heat sources are not suitable.

Displacement ventilation diffusers must not be placed such that the supply air flows towards heating devices.

4.2 Choice of diffuser

The likelihood of draught problems is greatly influenced by the choice of diffuser. One must choose a diffuser with the right amount of mixing between the room air and supply air. The air velocity near the diffuser may also create problems if induction rates are high. It is recommended to use only diffusers from manufacturers for which reliable documentation exists. Such diffusers are generally designed with special aerodynamic features to reduce draught problems. Nordtest has defined a performance documentation method [4]. Improvised diffusers made of a simple grille or perforated metal sheet can cause more draught along the floor. In cases where the manufacturer cannot guarantee performance figures, a full-scale laboratory mock-up of the specific room application should be built and tested.

4.3 Control and automation

During the heating season, supply air temperature is kept constant (at its maximum value, e.g. 20°C), and thus is not regulated according to the room thermostat.

During the cooling season, the supply air temperature should be controlled by the room thermostat, but with the limitations that the individual system sets. The supply temperature must not go below its minimum value, e.g. 18°C (see point 3.1.1). When a chilled ceiling is present, the displacement supply air is kept constant (under-temperature not exceeding 6°C), whilst the ceiling’s cooling output is regulated to control the room temperature. This minimizes draught-risk.

Displacement ventilation is well suited for variable air volume (VAV) applications. The ventilation rate is controlled according to the temperature in the occupied zone or according to the air quality. When the dominant pollutant source is people, CO_2 sensors are ideal for controlling air quality. Compared to constant air volume (CAV) systems, VAV systems have lower running-costs and lower draught risk during periods of reduced ventilation rate.

For more guidance on controls for displacement ventilation, see [1] & [6].

4.3.1 Sensor location

For rooms with normal ceiling height, the room air temperature sensor should be located 0.2 ~ 0.5 m above the floor for rooms with floor-standing diffusers, or just above the floor in the case of under-floor ventilation systems. This low location reduces swings in the supply air temperature and resulting draught discomfort.

For rooms with normal ceiling height, an air quality sensor (e.g. CO_2) should be located at breathing height (or up to 20 cm below if occupants are static), i.e. between 0.9 and 1.5 m above the floor for rooms with predominantly sitting or standing occupants. In tall rooms, the air quality sensor is located at the highest likely point of the occupied zone.

5 Commissioning, operation & maintenance

5.1 Balancing / commissioning

The flow rates in the ventilation system must be properly balanced before it is handed over to the user. The system must therefore be designed to enable flow measurement and balancing of each individual diffuser. To prevent too many balancing points, it is advantageous to build the duct system in symmetric groups (bifurcated). Balancing can thus be done in groups, with one damper for each group.

The ventilation system must be cleaned before it is handed over to the user.

For more guidance on commissioning, see [7].

5.2 Operation & maintenance

The ventilation system should be handed over with a complete and straightforward manual for maintenance and daily operation. Correct operation & maintenance requires regular attendance, checks, and maintenance.

6 References

[1] *Displacement ventilation in non-industrial premises*. Håkon Skistad (ed.). Brussels : Federation of European Heating and Air-conditioning Associations (REHVA), 2002.

[2] S. Holmberg & Q. Chen. *Air flow and particle control with different ventilation systems in a classroom*. Indoor Air, 2003; 13; pp.200-204

[3] K. Fitzner. *Displacement ventilation and cooled ceilings, results of laboratory tests and practical installations*. Proceedings Indoor Air 1996, Nagoya. Japan, Vol.1, p.41-50

[4] Nordtest method: *Air Terminal Devices: Aerodynamic Testing and Rating at Low Velocity*. Finland : Nordtest, 2003. Available at http://www.nordtest.org/

[5] T.H. Dokka & P.O. Tjelflaat. *Simplified models for prediction of vertical contaminant and temperature stratification in displacement ventilated rooms. Part 1 : Derivation*. 2000, Norwegian University of Science & Technology.

[6] *CIBSE Guide H : Building control systems*. London : Chartered Institution of Building Services Engineers. 2000. http://www.cibse.org/

[7] *CIBSE commissioning codes* (a series of guidance documents). Chartered Institution of Building Services Engineers, London, http://www.cibse.org/

[8] ISO 7730. *Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort.*

[9] CEN CR-1752. *Ventilation for buildings – design criteria for the indoor environment*

[10] A.K. Melikov & J.B. Nielsen Local thermal discomfort due to draft and vertical temperature difference in rooms with displacement ventilation. *ASHRAE Transactions*. 1989 pp 1050-1057.

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The **Air Infiltration and Ventilation Centre** is funded by the following seven countries: Belgium, Czech Republic, France, Greece, the Netherlands, Norway and United States of America.